Coupling MM5 with ISOLSM: Development, Testing, and Applications

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1. INTRODUCTION

Surface water and energy fluxes are tightly coupled with CO_2 exchanges between the ecosystem and atmosphere. Other surface-to-atmosphere trace-gas exchanges of interest in climate change research (e.g., N_2O, CH_4, $C^{18}OO$, and $H_2{}^{18}O$) are also strongly impacted by surface energy exchanges. Further, land-use change has large effects on the surface energy balance and therefore the exchanges of these trace gases. To investigate these issues at the regional scale we have coupled MM5 (Grell *et al.* 1995) with ISOLSM (Riley *et al.* 2002, Riley *et al.* 2003), a land-surface model based on LSM1 (Bonan 1995). LSM1 simulates the vegetation response to atmospheric water vapor, CO_2, and radiation, thereby computing consistent estimates of transpiration, photosynthetic, and net ecosystem CO_2 exchange fluxes. Soil water, soil temperature, and autotrophic and heterotrophic respiration are also calculated in the multi-layer soil model. In addition to the capabilities of LSM1, ISOLSM simulates gaseous (CO_2, $C^{18}OO$, N_2O, NO, $H_2{}^{18}O$, H_2O) and aqueous (C, $H_2{}^{18}O$, NO_3^-, and NO_2^-) fluxes within the soil column and $H_2{}^{18}O$ and $C^{18}OO$ exchanges between the atmosphere and vegetation. The ^{18}O predictions in ISOLSM have been successfully evaluated in a C_4 grassland (Riley *et al.* 2003). Here we describe the integration of the models and their implementation on NERSC's 6656-processor IBM POWER3 SMP. We also describe model comparisons with the (1) OSULSM land-surface model (Chen and Dudhia 2001) currently integrated in MM5 and (2) FIFE dataset (Betts and Ball 1998), a 3-year compilation of surface fluxes, soil moisture, and soil temperature averaged over a 225 km^2 area in Kansas. Finally, we describe a modeling investigation of the impact of winter wheat harvest on surface fluxes, near-surface air temperatures, and regional climate in the Southern Great Plains ARM-CART region. We intend to use the modeling approach described here to estimate regional-scale CO_2 exchanges between the land surface and atmosphere for a range of meteorological and land-use conditions.

2. MODEL INTEGRATION

The integration of LSM1.0 with MM5 was accomplished via the established interface for the OSULSM, with changes in the interface to account for partitioning shortwave radiation between diffuse and direct components, spatially- and temporally-dependent vegetation dynamics (i.e., leaf area index), and changes in soil type characterization.

The model simulations are performed on NERSC's SMP machine. The SMP has a distributed memory system with 380 compute nodes, each with 16 processors and 16 to 64 GB of memory, resulting in a peak machine speed of 10 Tflops s^{-1}. Comparisons indicate the MPP (pure MPI) and sequential simulations are bit-for-bit identical using compiler option -O3 (but not -O3 -qarch=auto). We coupled the LSM1.0 with MM5 model by revising the included MPP library and MPP object files to accommodate two different model source styles. The speedup of our model configuration on 64 processors is about a factor of 36. The runtime for a one-month simulation is about 15 and 50 minutes for domains 1 and 2 (described below), respectively. We also created job submission scripts that do automatic model I/O from the NERSC high performance storage system (HPSS) and obtain model input from NNRP data.

3. MODEL CONFIGURATION

We used the standard initialization procedure for MM5v3.5, which applies first-guess and boundary condition fields interpolated from NCEP reanalysis data to the outer computational grid. Simulations were performed with a coarse grid of 100×100 km (54×68 grid points spanning the 48 contiguous states) and a one-way nesting to

10×10 km resolution (41×41 grids) centered over either the FIFE area (for testing) or the ARM-CART region. In the vertical, we used 18 σ-layers between the 100 mb top and surface. The following physics packages were used in the simulations: Grell convective scheme, simple ice microphysics, MRF PBL scheme, and the CCM2 radiation package.

4. MODEL TESTING

We first tested the coupled MM5-ISOLSM model by comparison to data collected during the FIFE campaign (Betts and Ball 1998). This series of experiments was conducted over the Konza prairie in Kansas during 1987-1989. For the results shown here we applied the calculated 30-minute spatial averages over the 15×15 km study area. Figure 1 shows comparisons between measurements and predictions from MM5 coupled with the ISOLSM and OSULSM land-surface models during June, 1987 for: (a) latent heat flux; (b) sensible heat flux; and (c) ground heat flux. Not shown are comparable comparisons between simulations and observations for three months each in 1987, 1988, and 1989. Generally, the ISOLSM predictions of surface energy fluxes were comparably or more accurate than those using the OSULSM land-surface model. The predictions are sensitive to the initial soil moisture, so that comparisons between modeled and measured values should be made after a model spin-up of at least a few days.

Surface skin temperature and 2 m air temperature were adequately but less accurately simulated than the surface energy fluxes (Figure 2). In the first two weeks of June both land-surface models under-predicted peak surface skin temperatures by up to 4 °C. Air temperature at 2 m was consistently underestimated by up to 3 °C in both models during the first two weeks. In the final week, nighttime temperatures were over-predicted by both models.

We note that comparisons of this kind between land-surface models coupled to regional-scale meteorological models can be problematic. Errors in simulation of atmospheric processes (e.g., vapor transport, cloud parameterization, radiation dynamic, or PBL dynamics) will propagate to the land-surface model and may impact differently the land-surface energy exchange predictions of each land-surface model. Also, the FIFE dataset is calculated as a spatial average over 225 km^2 assembled from data from a limited number of stations (22 in 1987, 10 in 1988, and 14 in 1989). Thus the dataset may not accurately capture the spatial heterogeneity in fluxes present in the area at all times. Still, the FIFE study provides a valuable dataset from which to evaluate distributed land-surface models.

5. SIMULATION AND IMPACTS OF WINTER WHEAT HARVEST

The coupled MM5-ISOLSM model was applied to the ARM-CART region to examine the effects of winter wheat harvest on land-surface energy, water, and trace-gas fluxes and regional climate. Winter wheat was chosen because it accounts for about 20% of the ARM-CART land area.

Two harvest scenarios were performed. In the "early harvest" scenario, winter wheat was harvested on June 4, 1987 (JD 155). In the "late harvest" scenario, winter wheat was harvested on July 5, 1987 (JD 186). These dates represent the range of winter wheat harvest in Oklahoma (USDA 1997). The simulations extended over a two-month period from June 1st to July 31st; harvest was simulated by setting the land-surface type to bare soil. Differences between the scenarios are presented relative to the late harvest scenario, i.e., as early harvest results – late harvest results.

Differences in latent and sensible heat fluxes, 2 m air and soil temperatures, and precipitation varied over the two-month simulation (Figures 3 and 4). Four distinct time periods are evident in these two figures. During the first three days after harvest (JD 155-158), midday latent heat fluxes increased by about 24 W m^{-2}, while sensible heat fluxes declined by about 9 W m^{-2}. During these three days much of the soil moisture in the top 20 cm of soil was lost to the atmosphere via evaporation. Soil temperature changed slightly and midday 2 m air temperature declined by about 0.3 °C due to the decreased sensible heat flux. No precipitation fell during this period.

On Julian days 158-170, the second period, spatially averaged midday latent heat fluxes decreased by about 37 W m^{-2}, as transpiration was eliminated and evaporation was sharply reduced in the harvested area. During this period the sensible heat flux increased by about 30 W m^{-2}. As a result, midday 2 m air temperature increased by about

0.7 °C. Midday soil temperatures also increased slightly (0.4 °C) due to the drier soils.

A significant change occurred during the third period (JD 170-185) that was associated with an increase in precipitation in the June harvest scenario. On average, midday latent heat fluxes increased ~22 W m^{-2} in the early harvest scenario as a result of the relative increase in precipitation in the harvested region.

The second harvest occurred on JD 185. During this fourth period surface fluxes, air and soil temperatures, and soil moisture levels rapidly converged between the two scenarios. This convergence indicates that the system has relatively little memory of the early harvest.

Changes within the harvested areas are substantially larger than the regionally averaged results suggest (Figure 5). Patterns in the harvested areas drive the regionally averaged differences shown in Figures 3 and 4. Also, there are some edge effects. For example, latent heat fluxes increased and sensible heat fluxes decreased in adjacent areas due to the drier air being advected from the harvested region. Averaged over the two-month simulation, though, this edge effect was relatively small.

6. CONCLUSIONS

We have successfully coupled MM5 and the land-surface model ISOLSM and tested the coupled model against the 3-year FIFE dataset of surface fluxes, soil and air temperatures, and soil moisture. The coupled model allows us to estimate surface energy and water fluxes that are consistent with ecosystem CO_2 exchange. Further, the soil advection and diffusion sub-models allow us to simulate the impacts of regional-scale meteorology on distributed fluxes of other trace gases of interest.

Simulations of winter wheat harvest in the ARM-CART region indicate that widespread harvesting substantially impacts both regionally averaged and local surface fluxes, 2 m air and soil temperatures, and soil moisture. In the future, we intend to use the coupled model to investigate the coupling between human-induced landuse change and regional climate, predict regionally-distributed estimates of CO_2 exchanges, and investigate the practicality of estimating distributed trace-gas fluxes from atmospheric measurements.

7. FIGURES

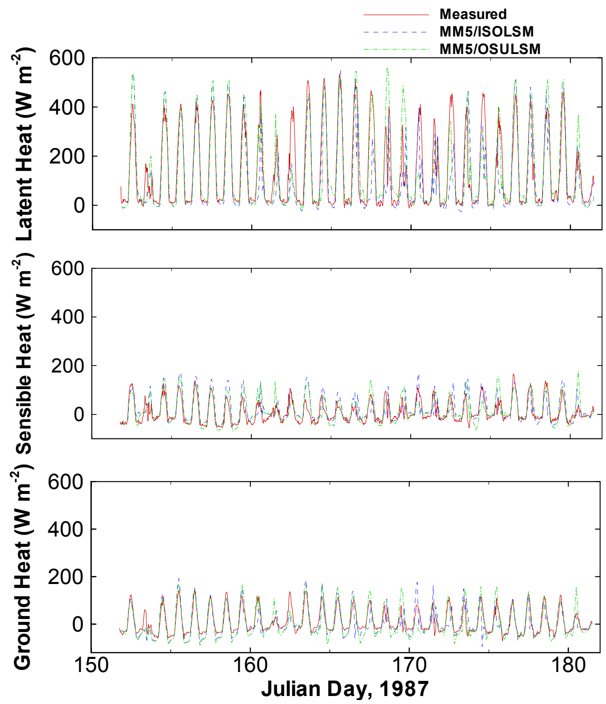

Figure 1. Comparison between FIFE measurements and the MM5/ISOLSM and MM5/OSULSM predictions for June 1987. Shown are the (a) latent, (b) sensible, and (c) ground heat fluxes.

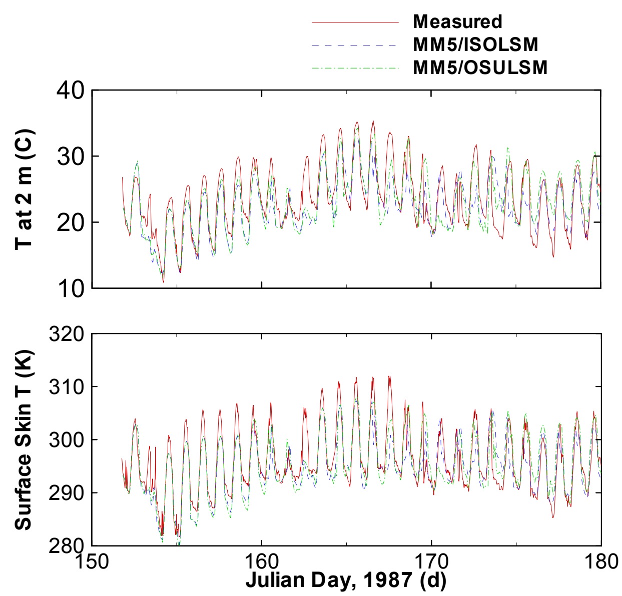

Figure 2. Comparison between FIFE measurements and the MM5/ISOLSM and MM5/OSULSM predictions for June 1987. Shown are the surface skin and 2 m air temperatures.

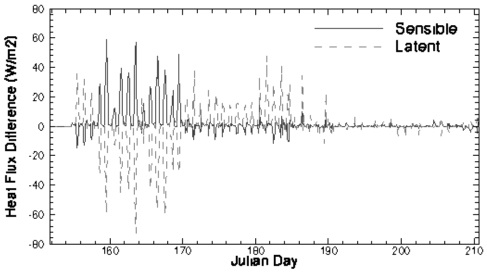

Figure 3. Differences in latent and sensible heat fluxes averaged over the ARM-CART region. The early winter wheat harvest occurred on JD 155. Differences between scenarios are presented relative to the late harvest scenario, i.e., as early harvest results – late harvest results.

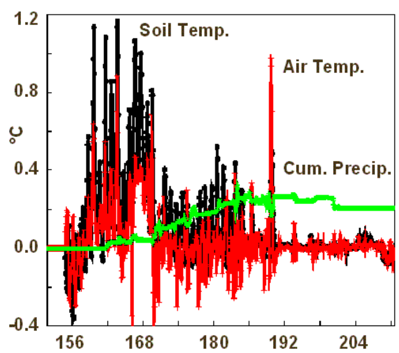

Figure 4. Differences in 2 m air and soil temperatures and precipitation averaged over the ARM-CART region. Differences between the scenarios are presented relative to the late harvest scenario, i.e., as early harvest results – late harvest results.

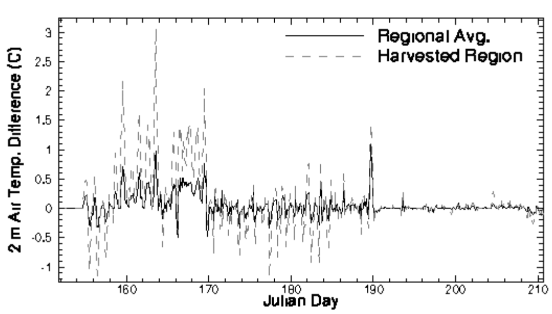

Figure 5. Differences in 2 m air temperature in the harvested area and averaged over the entire region. As expected 2 m air and soil temperatures were substantially higher in the harvested area.

8. REFERENCES

Betts AK, Ball JH (1998) Fife Surface Climate and Site-Average Dataset 1987-89. *Journal of the Atmospheric Sciences,* **55**, 1091-1108.

Bonan GB (1995) Land-atmosphere interactions for climate system models: Coupling biophysical, biogeochemical, and ecosystem dynamical processes. *Remote Sensing of Environment,* **51**, 57-73.

Chen F, Dudhia J (2001) Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Monthly Weather Review,* **129**, 569-585.

Grell G, Dudhia J, Stauffer D (1995) A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). TN-398+STR, NCAR, Boulder, CO.

Riley WJ, Still CJ, Torn MS, Berry JA (2002) A Mechanistic Model of $H_2^{18}O$ and $C^{18}OO$ Fluxes between Ecosystems and the Atmosphere: Model Description and Sensitivity Analyses. *Global Biogeochemical Cycles,* **16**, 1095-1109.

Riley WJ, Still CS, Helliker BR, Ribas-Carbo M, Verma S, Berry JA (2003) Measured and modeled $d^{18}O$ in CO_2 and H_2O above a tallgrass prairie. *Global Change Biology,* **Submitted**.

USDA (1997) Usual planting and harvesting dates for U.S. field crops. Agricultural Handbook No. 628, United States Department of Agriculture.